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# CHARACTERIZATION OF THE ENVIRONMENT DURING SAX04: PRELIMINARY RESULTS

Michael D. Richardson[a], Kevin B. Briggs[a], Allen H. Reed[a], W. Chad Vaughan[a], Michael A. Zimmer[a], L. Dale Bibee[a], and Richard I. Ray[b]

[a] Marine Geosciences Division, Naval Research Laboratory, SSC, MS 39529-5004.
[b] Oceanography Division, Naval Research Laboratory, SSC, MS 39529-5004.

Michael D. Richardson, Marine Geosciences Division, Naval Research Laboratory, SSC, MS 39529-5004; FAX: 01 228-688-5752; E-mail: mrichardson@nrlssc.navy.mil

***Abstract:*** *The Sediment Acoustic Experiment (SAX04) was conducted on a sandy sediment 1-km offshore of Ft. Walton Beach, Florida, September-November, 2004. The objectives of SAX04 were to provide a fundamental understanding of high-frequency acoustic-bottom interactions sufficient to predict acoustic scattering from the seafloor, penetration of acoustic energy into the seafloor, and propagation of acoustic energy within the seafloor. For these acoustic topics a thorough characterization of seafloor properties is required. The specific objectives of the team from the Naval Research Laboratory were 1) to provide statistical characterization of the environmental properties, especially the roughness and sediment volume properties; 2) measure and model the dispersive behavior of sediment sound speed and attenuation over the 1-400-kHz frequency band; 3) conduct in situ manipulative experiments to determine the effects of changing seafloor roughness on high-frequency acoustic scattering; 4) determine the effects of biological, geological, and hydrodynamic processes on the spatial and temporal distribution of sediment physical, geotechnical and geoacoustic properties; 5) develop predictive empirical and physical models of the relationships among those properties; and 6) derive a fundamental understanding of the effects of sediment microstructure (porometric and grain properties) on fluid flow and geoacoustic properties. During the 60-day experiment NRL divers made 126 dives manipulating seafloor roughness and discrete scatters, measuring seafloor properties and roughness in situ, deploying equipment of the seafloor, and collecting a variety of sediment samples. Preliminary results from SAX04 are presented.*

***Keywords:*** *SAX04; geoacoustics; roughness; high-frequency experiments; scattering*

## 1. INTRODUCTION

The SAX04 (Sediment Acoustics Experiment 2004) was conducted on a medium sand substrate in 16-17 meter water depth in the northeastern Gulf of Mexico during September-November 2004. The SAX04 long-range objectives are to provide a fundamental understanding of high-frequency acoustic-bottom interactions sufficient to predict acoustic scattering from the seafloor, penetration of acoustic energy into the seafloor, and propagation of acoustic energy within the seafloor. These resultant acoustic models support performance prediction and tactical use of MCM sonar including buried mine detection by Synthetic Aperture Sonar (SAS), and support shallow-water ASW sonar systems. SAX04 followed the structure of the highly successful SAX99 experiment conducted in the fall of 1999 about 1-km south of the SAX04 site [1-3]. The role of the Naval Research Laboratory is to provide statistical characterization of the environmental properties, especially the physical and geoacoustic properties, roughness, and sediment volume properties, required to understand, model, and determine the relative importance of the dominant mechanisms controlling both penetration of high-frequency acoustic energy into the seafloor and scattering of high-frequency energy from the seafloor. Special emphasis was placed on the effect of sand ripples on SAS detection of buried targets. We also measured and modelled the dispersive behavior of sediment sound speed and attenuation over the 1-400-kHz frequency band. In situ manipulative experiments were conducted to determine the effects of changing seafloor roughness on high-frequency acoustic scattering and to characterize and model the effects of biological, geological, and hydrodynamic processes on the spatial and temporal distribution of sediment properties, especially the effects of biological processes on rates of degradation of sand ripples. These data will be used to improve predictive empirical and physical models of the relationships among those properties and to derive a fundamental understanding of the effects of sediment microstructure (porometric and grain properties) on fluid flow and geoacoustic properties.

During the 60-day experiment NRL divers made 126 dives manipulating seafloor roughness and discrete scatterers, measuring seafloor properties and roughness, deploying bottom-mounted systems, and collecting a variety of sediment samples for later laboratory analyses. We collected 58 diver cores to characterize sediment physical (porosity, bulk density, mean grain size) and geoacoustic properties (compressional wave speed and attenuation), 22 cores for permeability, 9 cores were impregnated with resin for subsequent characterization of pore structure with high-resolution CT-scanning. A total of 26 dives were devoted to manipulative experiments at the BAMS tower (40-kHz backscatter), including alteration of seafloor roughness and addition of discrete scatterers (spheres and disks); 6 dives were used create roughness and place discrete scatterers (marbles) in the field of view on the Applied Physics Laboratory's rail system (5-150-kHz backscatter); and 32 dives were devoted to manipulations in the view of sector and pencil beam sonar to measure rates of ripple decay caused by the activities of benthic fauna. Sand ripple heights were mostly measured manually by divers (17 2-meter profiles and 5 20-meter transects) as poor visibility precluded all but a few measurements of bottom roughness using stereo photography. Pore water salinity and gradients of pore water temperature were also measured. Compressional wave speed and attenuation at frequencies 25 to 200 kHz and shear wave speed were measured in situ at three sites using an in situ sediment geoacoustic measurement system (ISSAMS). An in situ resin impregnation system (ISEDS) was deployed at 5 sites in an attempt to provide relatively undisturbed samples for characterizing sediment volume

heterogeneity and for characterizing pore-grain structure with high-resolution CT-scanning. Sound speed and attenuation measurements were also made using a buried geophone/hydrophone array, recording signals from two low frequency acoustic sources at frequencies from 600 Hz to 20 kHz. The SAX04 experiment was partly delayed and interrupted by hurricanes and tropical storms. These storms created mud deposits indicated by areas of lower backscatter strength in side-scan images [Fig. 1]. Low visibility created by suspension of fine-grained sediments from these deposits hampered diving operations, especially for the manipulative experiments.

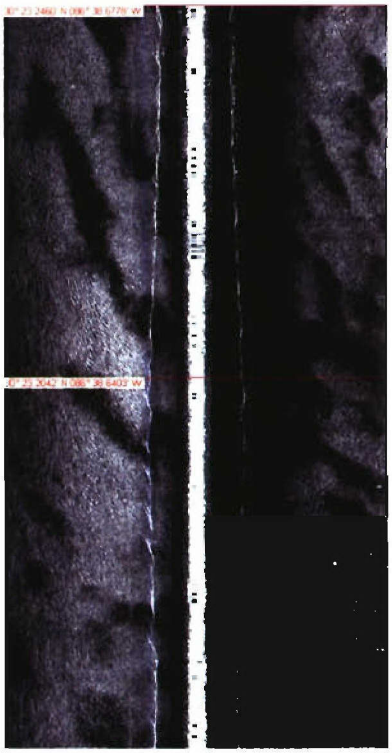

*Fig. 1: Side-scan sonar (300 kHz) image of the experimental site after the passage of Hurricane Ivan and just prior to deployment of BAMS and Dalpod towers. Ripples, with wavelengths of ~75 cm, are clearly evident. Mud deposits (10-50-m long) depicted as mottled areas often cover the sand ripples.*

## 2. SEAFLOOR PHYSICAL PROPERTIES

Divers collected a total of 58 5.9-cm-diameter cores from throughout the experiment area in order to characterize the means and the spatial and temporal variability of geoacoustic and physical properties in the SAX04 experimental area. These cores were allowed to equilibrate with ship laboratory temperature for 24 h before values of sediment sound speed and attenuation were determined at 1-cm intervals directly through the core liner. A pair of oil-filled transducers was used to transmit and receive 400-kHz compressional waves through the core and sediment. Values of sound speed (at 23°C, 35 ppt, atmospheric pressure) and sound

speed ratio (mean = 1775.6 m $s^{-1}$; 1.162 ) and attenuation (mean = 0.23 dB $m^{-1}$ $kHz^{-1}$) which are displayed in Figure 2, were within the range of values measured in other sandy sediments including sediments collected during the SAX99 experiments [1]. Lower values of sound speed are associated with muddy flaser deposits (Briggs et al., this volume Sound speed increased slightly with depth in the top 10 cm and, exclusive of the flaser deposits, had an overall coefficient of variation of 0.55 %. Values of attenuation varied little with depth and were slightly lower than those for sediment collected during SAX99 (mean = db $m^{-1}$ $kHz^{-1}$). The lowest values of attenuation were measured within mud lenses and the highest values of attenuation were measured at interfaces between mud lenses and sand.

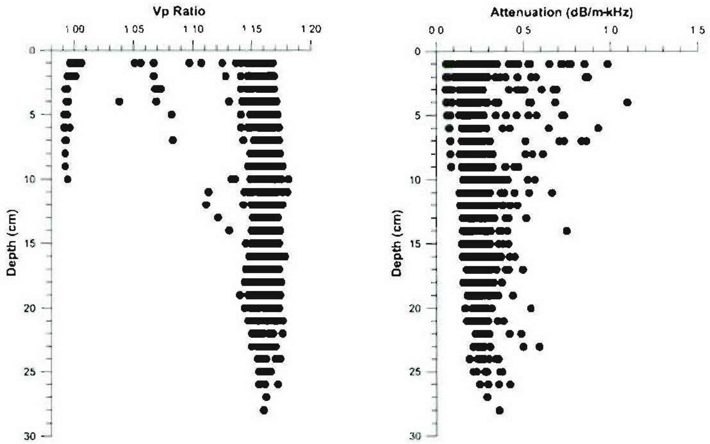


*Fig. 2: Depth profiles of sediment sound speed ratio and attenuation measured from diver-collected cores from SAX04. Values of low sound speed and low attenuation are associated with mud lenses created during and after hurricane and tropical storms. The highest values of attenuation were measured at interfaces of mud lenses and sand.*

Following the measurement of sediment sound speed and attenuation, 22 cores were selected for sectioning at 2-cm intervals for determination of sediment porosity, bulk density, and grain density; 12 of these sectioned cores were analyzed for grain size distribution. Sediment water content was determined by water loss after sectioned samples were dried in a drying oven at 105°C for 24 h. Porosity and density were calculated from values of water content and measurements of grain density with a Quantachrome Ultrapycnometer. Dried sand samples were subjected to wet-sieving for determination of the sand size-fraction and pipette samples were collected for determination of silt and clay fractions. Porosity (mean = 36.7 %) and bulk density (mean = 2.064 g $cm^{-3}$) varied little with depth. Mean grain size (mean = 1.50 phi) was slightly finer than sediment collected during SAX99 (mean = 1.27 phi). Short (13-cm) cores were also collected by divers for sediment permeability determination. The cores, in their entirety, were inserted into a modified Soil Test constant-head permeameter in order to approximate in situ measurements of percolation through intact sediment. Five separate determinations of constant-head flow rate were made on each core. Values of hydraulic conductivity varied from 0.56 to 4.65 x $10^{-2}$ cm $s^{-1}$ (approximately 0.53 to 4.34 x $10^{-11}$ $m^2$ in units of intrinsic permeability). The higher values of permeability were associated with cores with mud lenses. Sediments without mud layers had roughly the same permeability (0.93 to 4.56 $\times 10^{-2}$ cm $s^{-1}$) as sediments collected during SAX99 [1]. Pore water was collected by divers with a 30-cm-long cannula. Salinity and viscosity of the pore fluid was not measurably different than that of the overlying seawater suggesting considerable

transport across the sediment-water interface. Temperature decreased with depth (0-60 cm) in the sediment by nearly 4°C $m^{-1}$. The temperature gradient measured during SAX04 is the opposite of the gradient measured during SAX99 where the temperature increased with depth by 3-4°C $m^{-1}$. The decreasing temperature gradient suggests a mixing of colder, upwelled water into the sediment to at least 60 cm during Hurricane Ivan, followed by heating of the surface water, and then conduction of heat into the sediment from the overlying water.

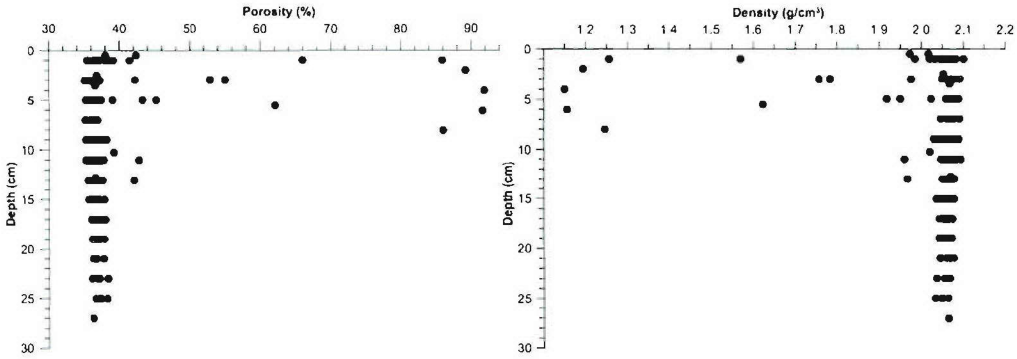


*Fig. 3: Profiles of porosity and bulk density measured from diver-collected cores from SAX04. The higher values of porosity and lower values of density are associated with lenses of mud created during and after hurricanes and tropical storms.*

Several of the long diver cores were impregnated on board ship with resin after measurement of acoustic properties. These cores have been scanned using a high-resolution CT-scanner in order to quantify fine-scale density heterogeneity, especially related to the distribution and structure of the mud flasers and sand laminae [see Briggs et al., this volume]. Later analysis of CT-images will be used to quantify fine-scale pore and grain structure, measure tortuosity, and enumerate and describe grain contacts (Fig 4). These data will be used to model acoustic behavior using contact mechanics and to calculate permeability using percolation and effective media theory [5].

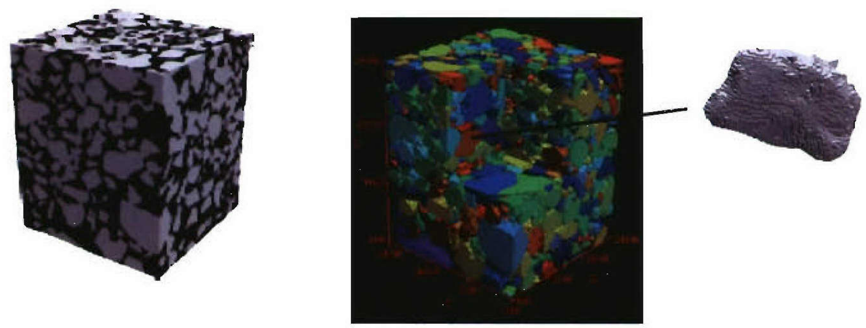

*Fig.4: CT scan of resin-impregnated sediment collected with a diver core during SAX99. The volume of scanned sediment is 82 $mm^3$ with a calculated porosity of 39 %. Pore network parameters are a mean inscribed pore radii is 58 $\mu m$, a mean inscribed throat radii is 42 $\mu m$, and the mean pore coordination number is 6.0. Mean grain size is 0.375 mm and average grain coordination number is 7.1. The individual grain has a volume of $2.5\times10^8$ $\mu m^3$, surface area of $2.0\times10^6$ $\mu m^2$, and aspect ratio of 2.2.*

## 3. IN SITU MEASUREMENT OF SEAFLOOR GEOACOUSTIC PROPERTIES

During SAX04 three separate measurement systems were used to make velocity and attenuation measurements over a frequency range from 0.6 kHz to 400 kHz. The SAX04 measurements built on those conducted during SAX99 [8] by focusing on making accurate measurements at the low end of this frequency range (< 20 kHz), where most of the Biot-predicted dispersion occurs and where the SAX99 measurements demonstrated large uncertainties. Two of the measurement systems, covering frequencies from 0.6 to 200 kHz, made in situ measurements of the sands within the first meter below the seafloor. For frequencies below 20 kHz, signals produced by two acoustic sources at a range of offsets and azimuths from the array were recorded on a diver-implanted hydrophone and geophone array. At frequencies from 25 to 200 kHz, measurements were made using a four probed piezoelectric array (ISSAMS). At the highest frequencies, from 60 to 400 kHz, values of velocity and attenuation were measured on sediments in 5 diver-collected cores with 4 separate pairs of oil-filled, piezoelectric transducers. Initial results for the sound speed demonstrate a very stable acoustic velocity of approximately 1780 m $s^{-1}$ above 10 or 20 kHz. Below 10 kHz the sound speed drops with decreasing frequency in a manner similar to that predicted by Biot theory [see Zimmer et al., this volume].

## 4. ACOUSTIC SCATTERING EXPERIMENTS FROM ARTIFICIALLY MANIPULATED SEAFLOOR SURFACES

During SAX99, a series of manipulative experiments were conducted in the field of view of bottom-mounted sonar systems [5-6]. These high-frequency (40 kHz) acoustic experiments involved scattering from artificial quasi-periodic roughness features (ripples) and from discrete targets (glass spheres and shells). The lack of total agreement between measured and predicted backscattering in these SAX99 experiments led to an expanded series of manipulative experiments during SAX04. Divers set up nine 2m-by-2m treatment areas within the acoustic field of view of the 40 kHz APL bottom-mounted autonomous measurement system (BAMS). Treatments consisted of varying abundances of glass spheres (10 – 80 $m^{-2}$ abundances of marbles with 1.75-cm radii) and aluminium disks (10 – 80 $m^{-2}$ abundances of 5-cm-diameter, 0.2-cm-thick disks provided by Tim Stanton, WHOI). The aluminium disks, meant to replicate small sand dollars, were placed either in horizontal or vertical orientations relative to the sediment surface. The quasi-periodic ripple fields were raked by divers using a straight-edge surface milled to create tine spacings (ripple wavelength) of 1.91-cm and 3.0-cm. Ripple fields were created parallel (180°), perpendicular (90°) and at a 30° angle to the incident path of the acoustic waves. In spite of the good intentions of both divers and acoustic experimentalists, nature intervened, adversely affecting the success of the manipulative experiments. Hurricane Ivan (September 15-17, 2004) delayed the deployment of the BAMS tower until 18 September and divers were not able to begin establishing the treatment areas until 27 September. Most of the initial experiments were conducted in conditions of very poor visibility (less than 30 cm). Mud deposited on the seafloor after Hurricane Ivan and resuspended during the resurrected remnants of Hurricane Ivan (September 24-25) and tropical storm Jeanne (September 26-27) created scattered surface mud deposits a few to tens of centimeters thick [see Briggs et al., this volume]. Several surface scattering experiments became volume scattering experiments after the glass spheres and aluminium disks disappeared below the sediment surface. A later storm (tropical

Storm Matthew, October 9th) covered the muddy deposits with sand creating flaser deposits with imbedded glass spheres and aluminium disks. The acoustic measurements were terminated on October 6, 2004 when the BAMS tower choked itself to death on its own cables. In spite of the experimental difficulties some preliminary conclusions can be drawn from acoustic images collected by BAMS (Kevin Williams and Darrell Jackson both of APL University of Washington, kindly provided the backscatter images). In no cases were the aluminium sand dollar replicates visible in the scattering images. Glass spheres were evident in most acoustic images at all levels of abundance. Scattering strengths decreased with time as the glass spheres became buried. After the experiments were completed, almost all of the glass spheres and aluminium disks were recovered by divers from the treatment areas, suggesting any changes in measurement backscatter strengths were not due to the loss of potential targets. Treatment areas that were raked with a 1.91-cm tine spacing perpendicular to the acoustic path had strong backscatter strengths which decayed rapidly with time. Treatment areas raked with 3.0-cm tine spacing had much lower scattering strengths. Treatment areas raked with either tine spacing (1.91- or 3.0-cm) at 180° or 30° to the incident acoustic path were not notably different than untreated areas.

A second set of manipulative experiments were conducted using glass spheres and raked surfaces in the acoustic field of view of transducers mounted on the APL rail system (see Williams et al., this volume). Two experimental treatment areas were established 10 m from the base of the rail system. Backscattering strengths (20-150 kHz) were measured as divers increased the abundance of glass spheres from 10 to 80 $m^{-2}$ and raked the other treatment area with a tine spacing of 1.91 cm at 30°, perpendicular and parallel to the path of the incident acoustic waves. These experiments were conducted in conditions of excellent visibility and the initial analyses of the raking data suggest good agreement between acoustic theory and measurements [Kevin Williams, personal communication].

## 5. OTHER MANIPULATIVE EXPERIMENTS

Seafloor manipulative and tracer experiments were conducted near a bottom-mounted tripod (referred to hereafter as the Dalpod) deployed by Alex Hay (Dalhousie University) The Dalpod used systems to measure surface waves and bottom currents, nearbed velocity and bottom stress, nearbed turbulence and suspended sediment as well as rotary- and pencil-beam sonar, video cameras, and laser scanners to monitor changes in seafloor roughness (see Hay, this volume). Divers created quasi-periodic ripple fields with tine spacing of 2, 4, 6, 8, and 10 cm in the field of view of the sonar, video, and laser imaging systems. Preliminary analyses of the data indicate a correlation between ripple size and rates of degradation, with smaller ripples (2-4-cm tine spacing) destroyed by bioturbation within a day or two and larger ripples (6-10-cm tine spacing) lasting for up to a week. Based on video observations, ripple degradation is the result of feeding and locomotion behavior of fish and larger invertebrates, such as sand dollars and starfish. The objectives of these manipulative experiments are to compare measurements and predictions of the rates of degradation of naturally occurring and artificially generated ripples by biological organisms in a sandy, inner-shelf environment subjected to infrequent storm events. The measurements of bedform degradation due to biological processes will be used to validate and test the predictive ability of the cellular automaton bioturbation model.

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